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EFFECT OF OXYGEN CONCENTRATION ON THE PERFORMANCE OF SYNTHETIC PARAFFINIC OILS IN SHORT TERM BEARING TESTS FROM 400° TO 500° F

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ABSTRACT

The effect of ambient oxygen concentration on the performance of a synthetic paraffinic oil with and without an oxidation inhibitor was studied in bearing tests at 400° to 500° F. Bearing torque increase was correlated with increases in lubricant viscosity due to lubricant oxidation. The viscosity and total acid number of the uninhibited oil increased as oxygen concentration increased. The viscosity increases were attributed to bearing operation in the presence of oxygen. Tests with the bearing not rotating produced relatively small increases in viscosity. The oxidation inhibitor significantly reduced oxidation of the oil at 400° F for oxygen concentrations up to 21 percent. Longer term bearing tests at 400° F show a limitation on the effective life (induction period) of the lubricant with the oxidation inhibitor.

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SUMMARY

The NASA high-temperature bearing test apparatus was used to test a synthetic paraffinic oil with and without an oxidation inhibitor. Angular-contact ball bearings (204-size) were run at outer-race temperatures of 400° to 500° F (477 to 533 K) and with oxygen concentrations in the test bearing chamber varying from less than 0.1 percent to approximately 21 percent by volume. The thrust load was 70 pounds (310 N) producing a maximum Hertz stress of 200 000 psi (1.38×10^9 N/m^2) on the inner race. The shaft speed was 10 600 rpm.

Bearing torque increases during the tests correlated with increases in lubricant viscosity due to lubricant oxidation. With the uninhibited synthetic paraffinic oil, both viscosity and total acid number increased as oxygen concentration increased. Increases in viscosity were attributed primarily to bearing operation in the presence of oxygen. Tests with the bearing not rotating produced relatively small increases in viscosity.

The oxidation inhibitor significantly reduced oxidation of the paraffinic oil for at least 6 hours at a bearing outer-race temperature of 400° F (477 K) and oxygen concentrations up to 21 percent. Longer term tests at 400° F (477 K) and 8-percent oxygen concentration show a limitation on the effective life of the oxidation inhibitor. This limitation depends on the past history of the bearing and the presence of an antiwear additive in the fluid.

INTRODUCTION

Bearing temperatures in the range of 400° to 600° F (477 to 588 K) are anticipated in advanced gas-turbine engines and accessory drive systems such as those related to high-performance supersonic aircraft (refs. 1 and 2). A reliable bearing-lubricant system is

required for these and other high-temperature, high-speed applications. A key to successful and reliable bearing operation at these conditions is a lubricant that will withstand these difficult environments.

New classes of liquid lubricants have been developed recently for extending the upper temperature limits of liquid lubricants (refs. 3 to 6). These lubricants have been extensively studied to determine their thermal stability, their oxidation and corrosion properties, their effect on rolling-element fatigue, and their elastohydrodynamic (EHD) film forming capabilities (refs. 7 to 12). These parameters define the lubricants' upper temperature limitations.

A high-temperature liquid lubricant that has shown good thermal stability and good EHD film forming capabilities up to 600° F (588 K) is a synthetic paraffinic oil with an antiwear additive. This lubricant has provided long life in full-scale bearing tests at temperatures up to 600° F (588 K) in a low-oxygen environment (less than 0.1 percent by volume) (refs. 7 to 11). However, the oxidative stability of this lubricant is in question. As a result, nearly all testing with this fluid has been with limited oxygen availability within the system. Such a system (inert system) for advanced turbine engines introduces difficult seal problems (refs. 12 and 13).

It is conceivable that this lubricant can be used at temperatures at or above 400° F (477 K) if the oxygen content of the gases in the system and/or the oxygen partial pressure are low enough to prevent an undesirable degree of oxidation. The addition of an oxidation inhibitor could improve the oxidative stability of this lubricant.

The objectives of the research reported herein are to determine the effects of variable ambient oxygen content on the degradation of the synthetic paraffinic lubricant with and without an oxidation inhibitor. Tests were performed with 204-size angular-contact ball bearings at temperatures up to 500° F (533 K) with a recirculating-type lubrication system. Bearing torque increase, viscosity increase, and total acid number were used as indicators of lubricant degradation.

APPARATUS

The high-temperature bearing test apparatus shown in figures 1 and 2 was used in this lubricant evaluation program. This tester is a modification of the tester described in reference 7. The test bearing is held in a housing that is heated by eight resistance-type cartridge heaters. The housing is supported by an externally pressurized gas bearing which, in turn, is supported by four rubber vibration mounts. The effects of minor misalinements and oscillations are thus minimized. The rotating inner race is mounted on a shaft driven by a gear belt and induction motor. A thrust load is applied through a load arm system with a dead weight.

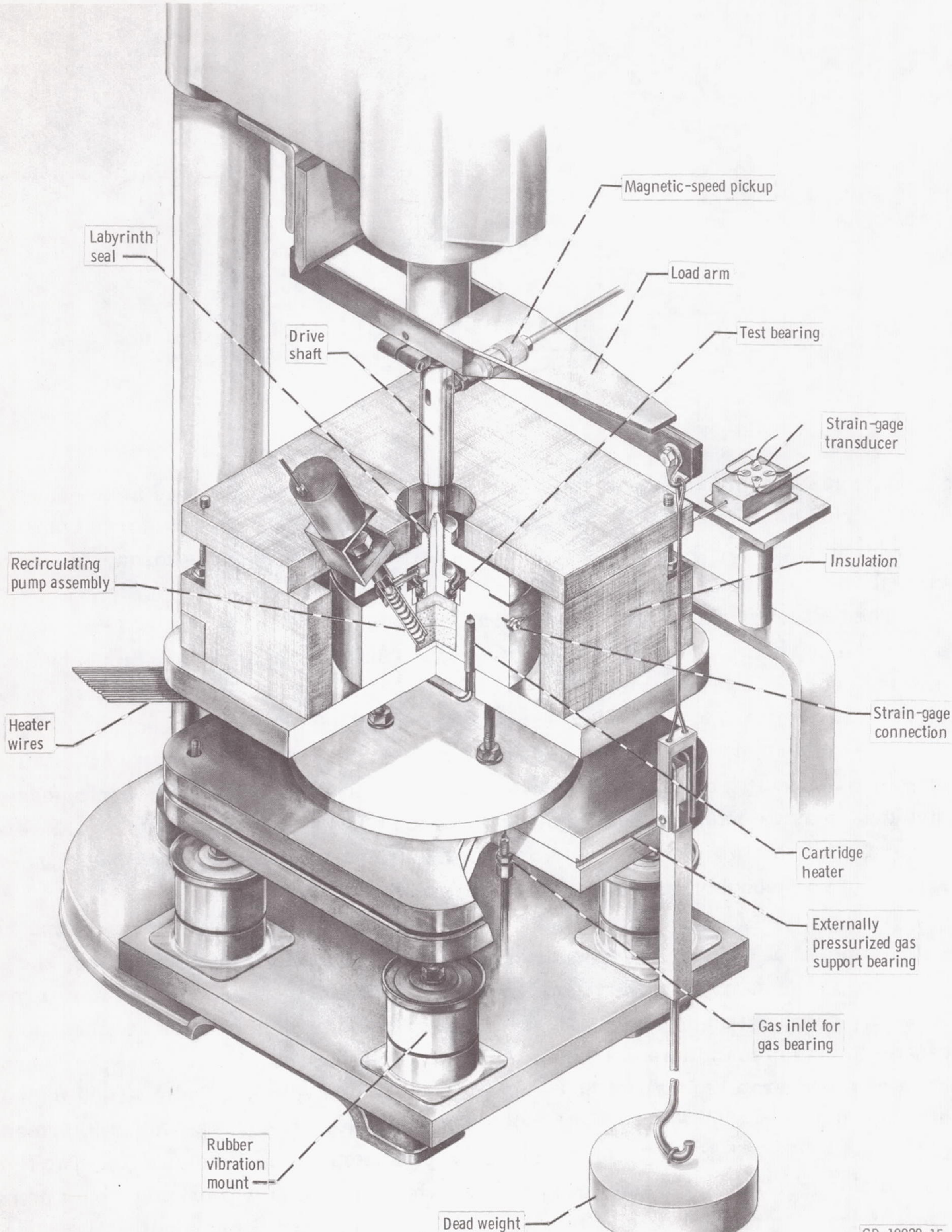

Figure 1. - High-temperature bearing test apparatus.

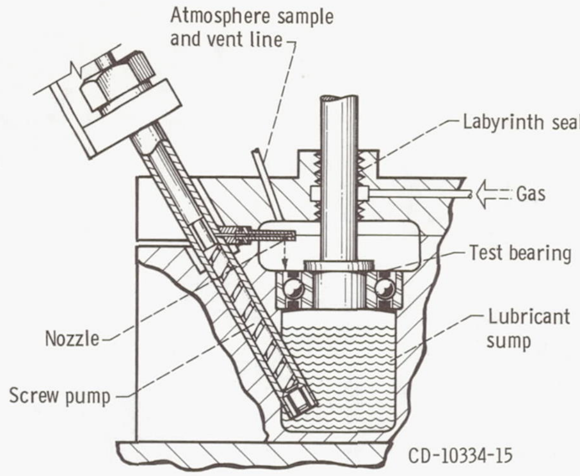

Figure 2. - Test bearing and lubricant recirculating pump.

The gas bearing allows torque measurement. A cable is attached at one end to the test-bearing housing and at the other end to a bridge-type strain-gage force transducer. The output of the force transducer (which is proportional to bearing torque) is recorded on a strip-chart recorder.

The test lubricant is recirculated from the sump through the test bearing by means of a screw pump. A single nozzle directs the lubricant stream at the annulus between the bearing retainer and the counterbored outer race (fig. 2). The pump is driven by a DC motor. Lubricant flow rate is calibrated and controlled by motor speed.

The atmosphere in the test-bearing chamber is controlled by a nitrogen gas-air mixture introduced at the labyrinth shaft seal (fig. 2). This atmosphere is continuously sampled and analyzed with a paramagnetic oxygen analyzer with a sensitivity of 0.1 percent of full scale for the two ranges of 0 to 5 percent and 0 to 25 percent by volume. The oxygen content is continuously recorded on a strip-chart recorder.

Critical temperatures are measured with thermocouples at several locations: the outside diameter of the outer race, the ambient gas in the test-bearing chamber, the bulk lubricant in the sump, and the pump housing. The bearing outer-race temperature is continusouly recorded on a strip-chart recorder. Periodic readings indicate that the lubricant in the sump maintains the same temperature as the outer race. The chamber ambient gas temperature is about 380° and 430° F (466 and 494 K) at outer-race temperatures of 400° and 450° F (477 and 505 K), respectively. The pump housing thermocouple is located at the outside of the junction of the pump housing and the nozzle. The temperature at this location is considered to be the lowest to which the lubricant would be exposed. This thermocouple reading is within a few degrees of the chamber ambient gas.

TEST BEARINGS

The bearings used in these high-temperature lubrication tests were 204-size (20 mm bore) angular-contact ball bearings of ABEC-5 specifications. The material of the balls and races was AISI M-1 steel of Rockwell C hardness 63±1. The retainer was of the machined inner-land-riding type made from annealed AISI M-1 material. Further specifications of the test bearings are as follows:

Ball diameter, in. (cm) 9/32 (0.715)
Number of balls 10
Contact angle, deg . . . . 17±1
Conformity, percent
Inner race 53
Outer race 54
Internal radial clearance, in. (cm) 0.0017 (0.0043)

TEST LUBRICANT

The lubricant tested in this program was a synthetic paraffinic oil. This lubricant has been extensively tested in previous work (refs. 7 to 11) both with and without an antiwear additive. It has shown good thermal stability and good elastohydrodynamic (EHD) film forming capabilities, and has provided long bearing life at temperatures up to 600° F (588 K) in a low-oxygen environment. In the present program, the synthetic paraffinic oil with the antiwear additive was tested both with and without an oxidation inhibitor. This oxidation inhibitor was added by the lubricant manufacturer and was considered the best

TABLE I. - VISCOSITY OF TEST LUBRICANTS (AS RECEIVED)

Lubricant	Kinematic viscosity, cS (or 10^{-6} m^2/sec), at -		
	100° F (311 K)	210° F (372 K)	400° F (477 K)
Synthetic paraffinic oil	442	39.8	5.7[a]
Synthetic paraffinic oil with oxidation inhibitor	484	41.8	5.7[a]

[a]Extrapolated.

available to provide oxidation-corrosion resistance in this lubricant. Table I shows the viscosity at 100°, 210°, and 400° F (311, 372, and 477 K) for the test lubricant with and without the oxidation inhibitor.

PROCEDURE

Each bearing was cleaned with solvent, dried, and installed in the apparatus. A new bearing was used for each test except as noted. An initial charge of 40 cc of unused lubricant was added to the lubricant sump. The test chamber was purged with nitrogen gas (~34 ppm O_2) as the heaters were energized and during warmup to test temperature. When an outer-race temperature of 300° F (422 K) was reached, a lubricant flow rate of 5 cc/min was started. A thrust load of 70 pounds (310 N) was applied which produced a maximum Hertz stress of 200 000 psi (1.38×10^9 N/m^2) on the inner race. The apparatus motor was started, driving the test bearing at 10 600 rpm. When the test temperature was reached, the desired atmosphere (oxygen percentage) was introduced, and the lubricant flow rate was increased to 14 cc/min. This flow rate was constant for all tests reported herein. During each test, bearing torque, oxygen content, and outer-race temperature were recorded on strip charts. Lubricant flow rate and bearing chamber ambient gas temperature were periodically recorded. Test duration was either 1, 5, or 26 hours at the desired test temperature.

After a test, the bearing was removed and inspected for surface appearance and deposit formations. The lubricant sample was carefully removed and analyzed. Viscosity at 100° and 210° F (311 and 372 K) and total acid number were measured. The system was thoroughly cleaned with solvent and dried in preparation for the subsequent test.

RESULTS AND DISCUSSION

Effect of Oxygen Concentration

Bearing tests were run with both the inhibited and the uninhibited synthetic paraffinic oil at oxygen concentrations from less than 0.1 percent (N_2 gas with ~34 ppm O_2) to approximately 21 percent by volume (100 percent air) with 204-size angular-contact ball bearings. Outer-race temperatures were 400°, 450°, and 500° F (477, 505, and 533 K). Although some change in the test lubricant occurred during initial 1-hour tests (see table II), no change in bearing torque could be detected.

It was found that 6- and 26-hour tests produced discernable differences in bearing torque and lubricant viscosity with the range of oxygen concentrations and temperatures discussed.

TABLE II. - PROPERTIES OF SYNTHETIC PARAFFINIC OIL AFTER 1-HOUR

BEARING TESTS WITH 8-PERCENT OXYGEN ENVIRONMENT

Oxidation inhibitor	Outer-race temperature		Viscosity, cS (or $\times 10^{-6}$ m^2/sec), at -		Viscosity increase at 100° F (311 K), percent	Total acid number
	$^{\circ}$F	K	100° F (311 K)	210° F (372 K)		
Yes	400	477	486.5	41.9	<1	0.09
Yes	450	505	502	42.9	4	.13
Yes	500	533	609	47.7	26	.82
No	500	533	557	44.8	26	.76

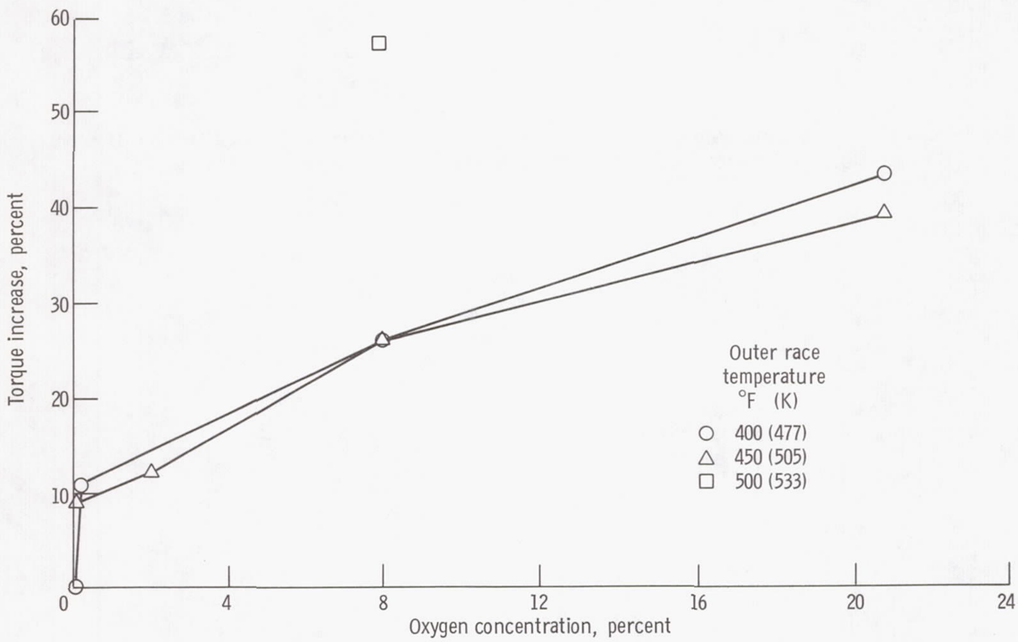

Figure 3. - Effect of oxygen concentration on bearing torque increase during 6-hour tests at 10 600 rpm and 70-pound (310-N) thrust load with synthetic paraffinic lubricant without oxidation inhibitor.

Uninhibited lubricant. - A series of bearings was run in 6-hour tests with the synthetic paraffinic oil with the antiwear additive but without the oxidation inhibitor at oxygen concentrations ranging from less than 0.1 to 21 percent and at outer-race temperatures of 400° and 450° F (477 and 505 K). Results of these tests showing bearing torque increase, viscosity increase, and total acid number after tests are shown in figures 3 to 5.

The torque increase shown in figure 3 is the percentage of increase in torque from the beginning to the end of each 6-hour test. Percent torque increase was used to compare the results, since each test at a particular condition was made with a new bearing.

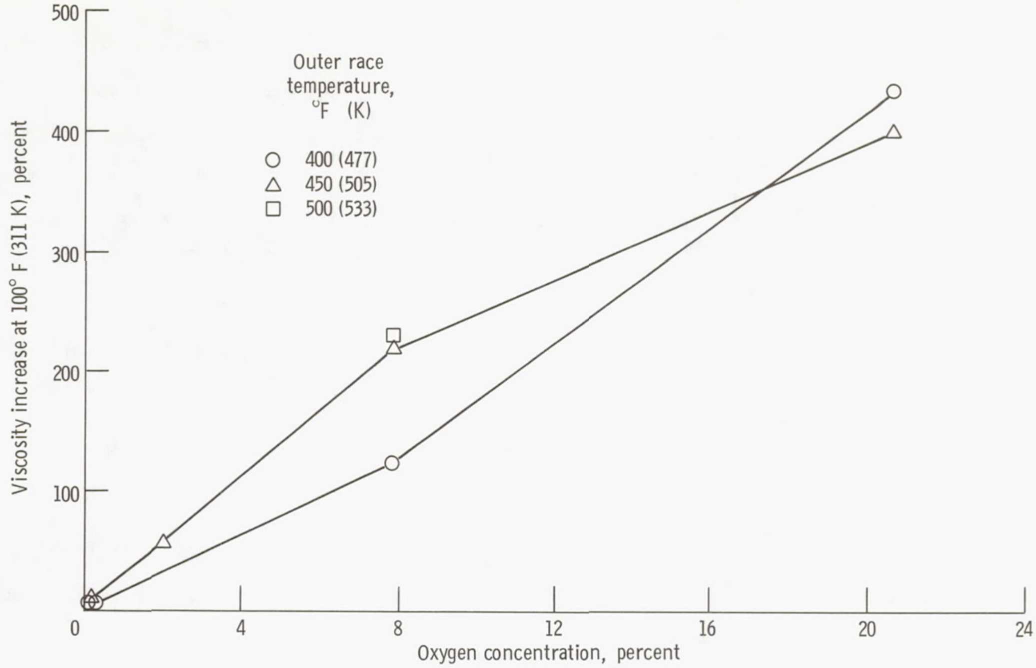

Figure 4. - Effect of oxygen concentration on viscosity increase of synthetic paraffinic oil without oxidation inhibitor during 6-hour tests at 10 600 rpm and 70-pound (310-N) thrust load.

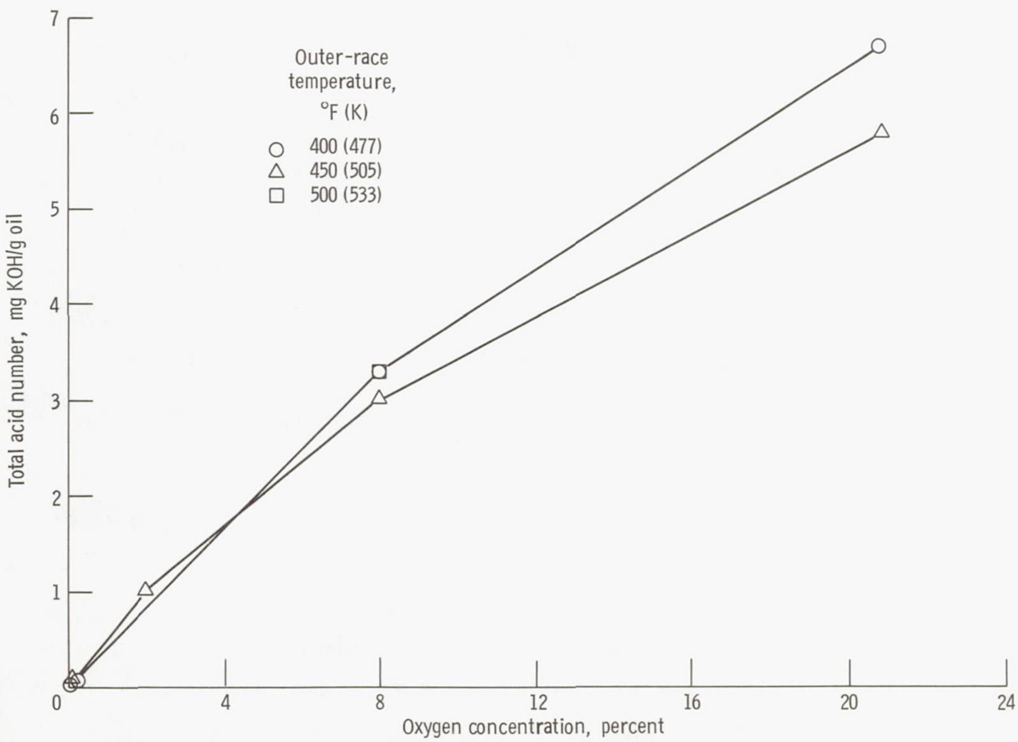

Figure 5. - Effect of oxygen concentration on total acid number of synthetic paraffinic oil without oxidation inhibitor after 6-hour tests at 10 600 rpm and 70-pound (310-N) thrust load.

Initial bearing torques for new bearings varied from approximately 0.10 inch-pound (0.011 N-m) to 0.15 inch-pound (0.017 N-m). In general, torque increase is greater for greater oxygen concentration. No difference can be seen between the results of 400° and 450° F (477 and 505 K) tests. One test at 500° F (533 K) outer-race temperature and 8-percent oxygen showed a higher torque increase than the lower temperature tests.

The results of the analysis of the lubricant samples from these tests are seen in figures 4 and 5. In figure 4, viscosity (measured at 100° F (311 K)) increases as oxygen concentration increases. Figure 5 shows a similar trend with total acid number of the used samples. As with the torque data, no difference between the results at 400° and 450° F (477 and 505 K) is seen. There is good correlation between lubricant degradation (as indicated by viscosity increase and acid number) and oxygen concentration. The increase in bearing torque appears to be a function of viscosity increase and thus a result of lubricant degradation.

Inhibited lubricant. - Another series of bearings was run with an oxidation inhibitor added to the synthetic paraffinic oil with the antiwear additive. Test conditions were

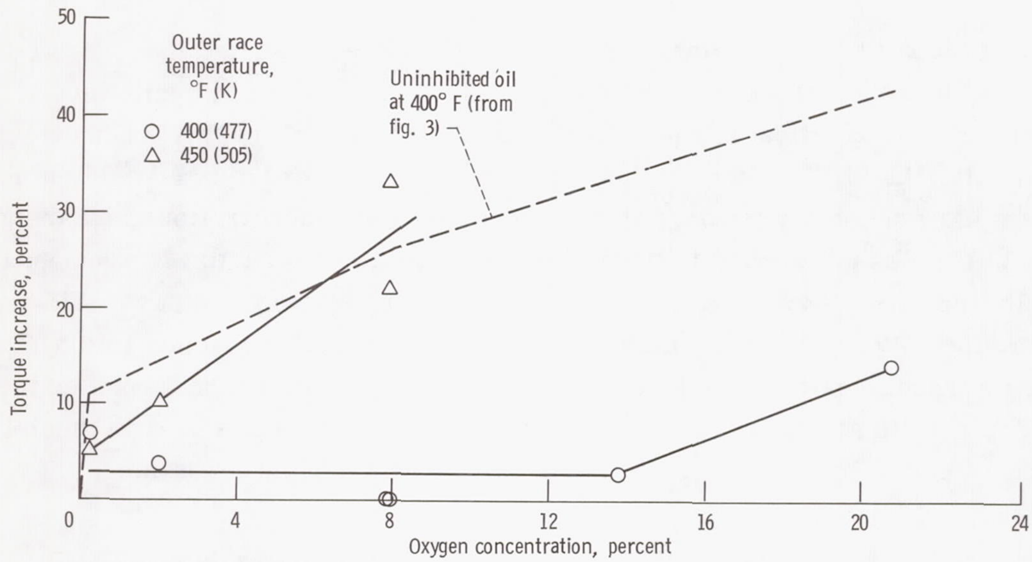

Figure 6. - Effect of oxygen concentration on bearing torque increase during 6-hour tests at 10 600 rpm and 70-pound (310-N) thrust load with synthetic paraffinic oil with oxidation inhibitor.

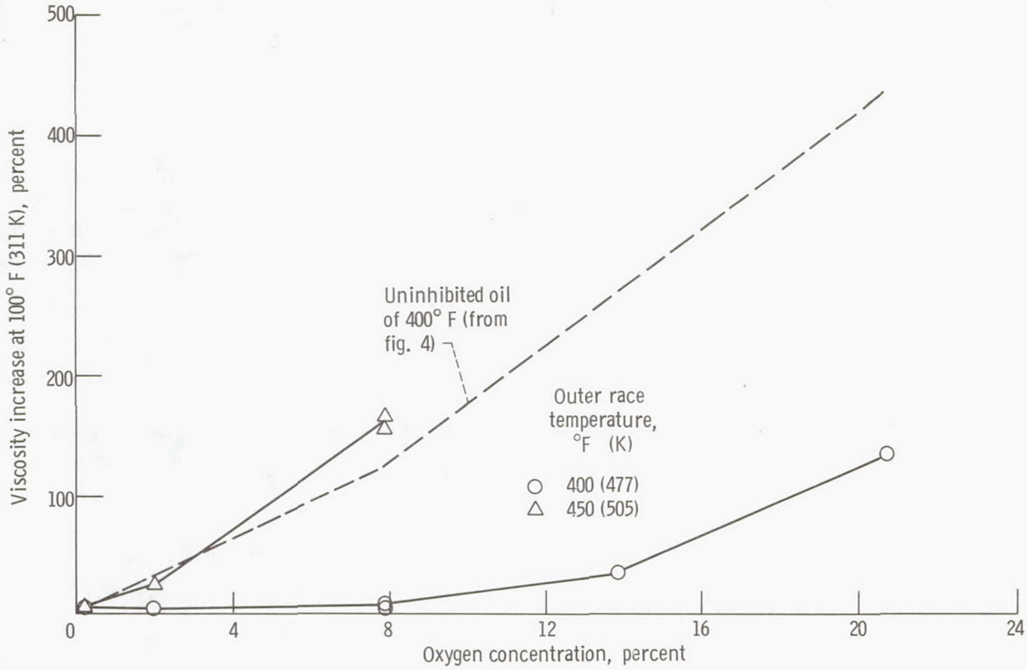

Figure 7. - Effect of oxygen concentration on viscosity increase of synthetic paraffinic oil with oxidation inhibitor after 6-hour tests at 10 600 rpm and 70-pound (310-N) thrust load.

identical to those with the uninhibited oil. These data are presented in figures 6 to 8. At 450° F (505 K) increases in torque, viscosity, and acid number show an effect of oxygen concentration nearly identical to the uninhibited oil. At 400° F (477 K), however, the oxygen concentration has little effect on increases in torque, viscosity, and acid number up to an 8-percent oxygen concentration. At 14-percent oxygen concentrations and above the oxidation inhibitor does not appear to be so effective. At 21-percent oxygen concentration, the viscosity increase, figure 7, was about 135 percent as compared to the 435-percent increase in viscosity of the uninhibited oil at the same condition (dashed line). These results indicate that the oxidation inhibitor is effective for at least 6 hours under these conditions. The results also indicate that the bearing torque increase seen in these tests is a good indication of lubricant viscosity increase due to lubricant oxidation.

Effect of Test Duration

The initial 1- and 6-hour bearing tests indicated that test duration had an effect on the oxidation of the lubricant. Because an oxidation inhibitor reacts chemically with oxygen in the process of retarding lubricant oxidation, the inhibitor should have some finite life after which it is no longer effective. This life has been termed an induction period (ref. 1).

A series of tests was run for longer duration (26 hr) at an outer-race temperature

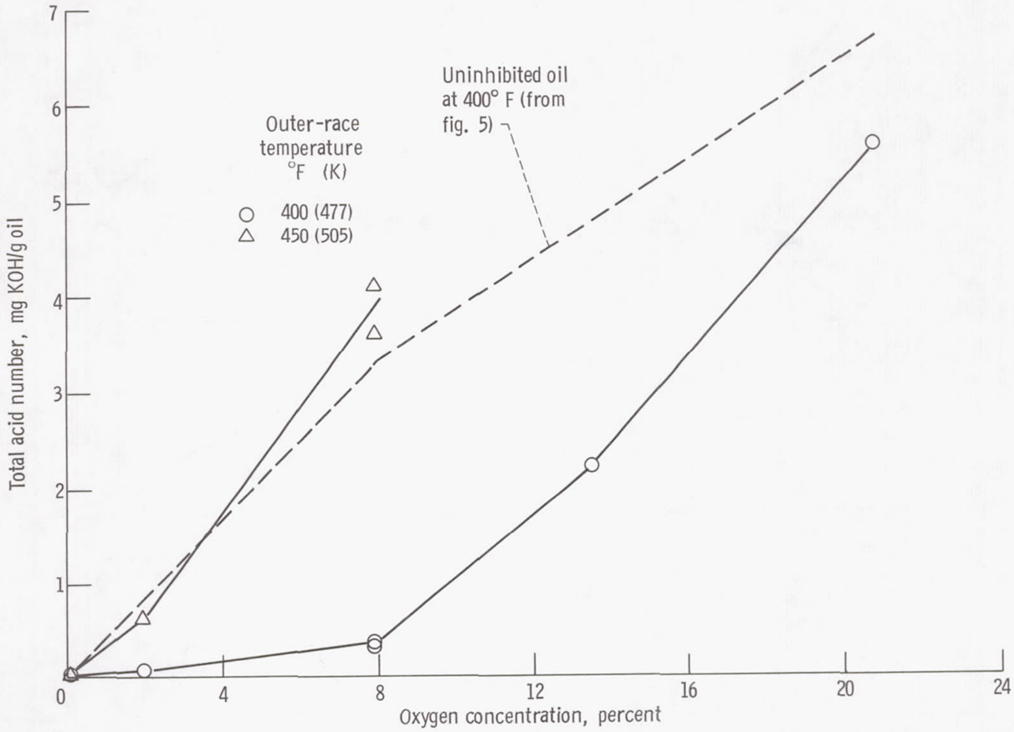

Figure 8. - Effect of oxygen concentration on total acid number of synthetic paraffinic oil with oxidation inhibitor after 6-hour tests at 10 600 rpm and 70-pound (310-N) thrust load.

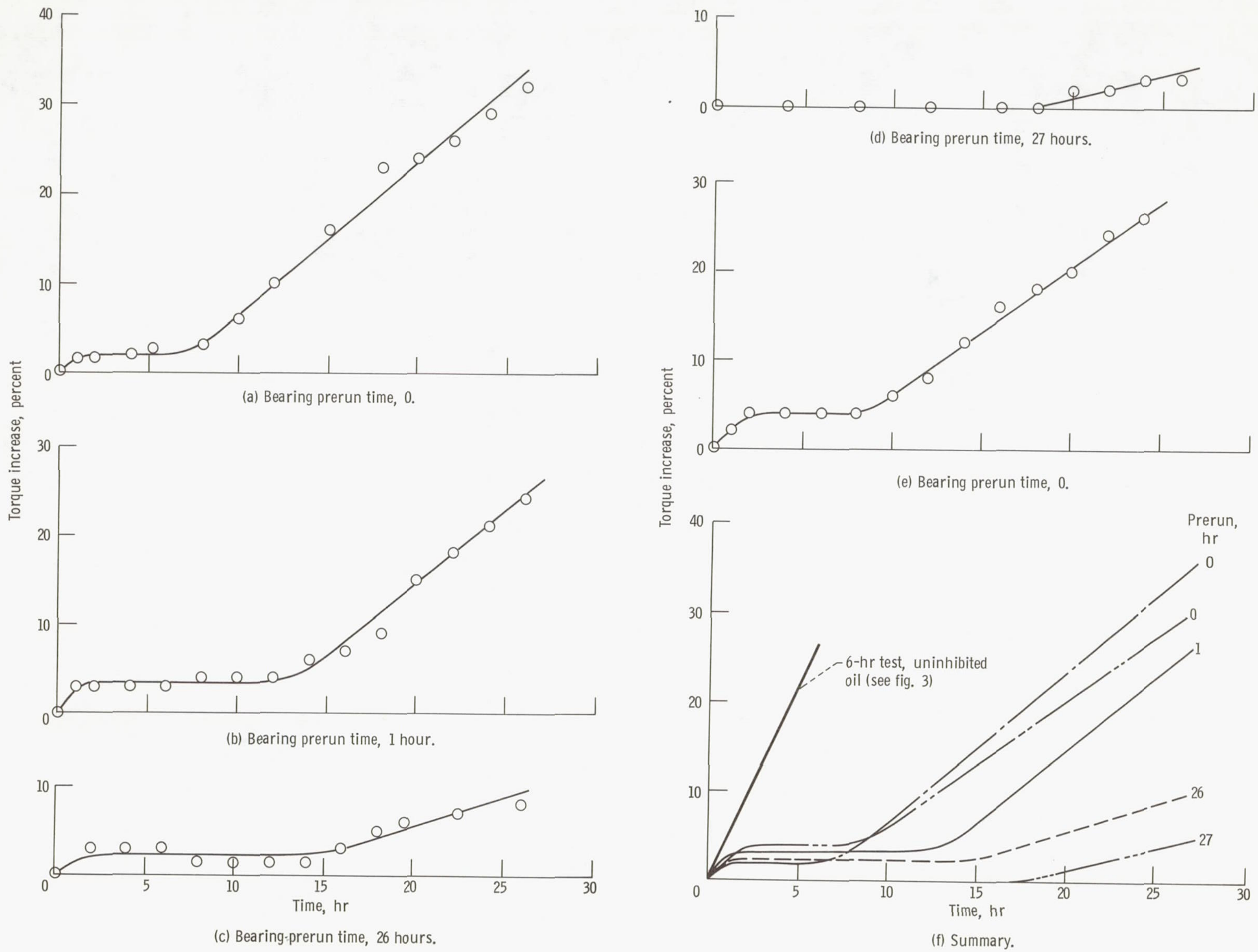

Figure 9. - Torque increase during test for several bearings run for 26 hours at 400° F (477 K) and 8-percent oxygen concentration with synthetic paraffinic oil containing antiwear additive and oxidation inhibitor.

of 400° F (477 K) and an 8-percent oxygen concentration with the inhibited oil. As seen in figure 9, the five separate tests gave a variety of results. An explanation for the difference in results can apparently be made in terms of the history of the test bearings. The results shown in figure 9(a) were obtained with an unused bearing. This test showed a break in the torque increase versus test time curve at about 6 hours (an induction period of 6 hr). The torque increased at a much higher rate after 6 hours, approaching that of the uninhibited oil, shown in figure 9(f) for comparison. Another test (fig. 9(b)) at these same conditions was made with a bearing that had been used for an initial 1-hour test. Initially, the torque increase-time curve was nearly identical to the results shown in figure 9(a), but the break occurred at about 12 hours. Subsequent tests with each of these two bearings, figures 9(c) and (d), show induction period of about 14 and 18 hours, respectively, and lower rates of increase after the breaks. Another test (fig. 9(e)) was run with a new bearing which showed a result identical with the initial test with a new bearing (fig. 9(a)). Thus the length of the induction period appears to depend on the past history of the bearing. This effect is believed to be due to the antiwear additive in the test lubricant. The function of this antiwear additive is to chemically react with the bearing surface and provide a boundary lubricating film. It is hypothesized that, as a result of this film formation, less bearing steel surface is available for its catalytic effect in the lubricant oxidation process. The oxidation of the lubricant is thus retarded. It is apparent that the bearings that were rerun in a second or third test were, in effect, precoated with the film provided by the antiwear additive.

It would be expected that more severe conditions of temperature, load, speed, or oxygen concentration would further limit the effective life of the oxidation inhibitor.

Effect of Bearing Rotation

A series of static tests was run to determine the effect of rotating the bearing on lubricant degradation. The lubricant was recirculated through the system at the desired temperature and oxygen concentration for a period of 6 hours. The results of these tests are shown in table III. No significant viscosity increases were noted. Tests with the bearing loaded and rotating at otherwise identical conditions showed much greater viscosity increases and higher acid numbers than these static tests (table III). The results of these static tests indicate that the operation or rotation of a bearing imposes a much more severe condition on the lubricant. The rotating bearing results in a more thorough mixing of the lubricant and the oxygen, repeated stressing of the lubricant, and the exposure of more bearing surface to the lubricant. Under these conditions, an increased rate of oxidation occurs.

TABLE III. - PROPERTIES OF SYNTHETIC PARAFFINIC OIL AFTER 1- AND 6-HOUR TESTS

WITH 8-PERCENT OXYGEN ENVIRONMENT

Oxidation inhibitor	Outer-race temperature		Viscosity increase at 100° F (311 K), percent			Total acid number		
	$^{\circ}$F	K	1-hr test	6-hr test	6-hr test (bearing not rotating)	1-hr test	6-hr test	6-hr test (bearing not rotating)
No	400	477	--	123	4.1	----	3.3	0.04
No	450	505	--	218	3.0	----	3.0	.23
No	500	523	26	230	---	0.76	3.3	----
Yes	400	477	<1	6.2	0	.09	.30	.03
Yes	450	505	4	156	2.3	.13	3.6	.02

Bearing Surface Appearance

The bearings were closely examined after each test. Deposit formations, if any, were very light. After the 6-hour tests at low oxygen concentration with the inhibited oil, the bearing surfaces were clean and bright, showing no discoloration from deposits or oxidation products. At higher oxygen concentrations with the uninhibited oil, some slight discoloration was noted on the exposed bearing surfaces. The inner- and outer-race ball tracks showed no surface damage in any test (including the 26-hr tests) and indicated that elastohydrodynamic lubrication was the predominant mode of lubrication throughout the range of test conditions.

GENERAL COMMENTS

The results of these tests indicate that the synthetic paraffinic oil without an oxidation inhibitor can be useful at temperatures of 400° to 450° F (477 to 505 K) only if the oxygen concentration is less than a few tenths of a percent. This correlates with results of references 9 and 10 which show highly successful operation with this lubricant up to 600° F (588 K) with a limited-oxygen environment (less than 0.1 percent by volume).

At 400° F (477 K) and 8-percent oxygen concentration, the oxidation inhibitor provided stable operation for at least 6 hours or as long as 26 hours depending on the history of the test bearing. These data show that this oxidation inhibitor can be effective in reducing oxidation under certain conditions if some degree of inertion is provided.

SUMMARY OF RESULTS

A synthetic paraffinic oil with an antiwear additive was tested with 204-size angular-contact ball bearings of AISI M-1 steel in a high-temperature bearing test apparatus. The oxygen concentration of the atmosphere within the test-bearing chamber was varied from less than 0.1 percent to approximately 21 percent by volume. The effects of the oxygen concentration on the lubricant at temperatures from 400° to 450° F (477 to 505 K) was studied. Test conditions were a thrust load of 70 pounds (310 N) producing a maximum Hertz stress of 200 000 psi (1.38×10^9 N/m^2) at the inner-race-ball contact and an inner-race speed of 10 600 rpm. The following results were obtained.

1. An oxidation inhibitor significantly reduced oxidation of the paraffinic oil in 6-hour tests at a bearing outer-race temperature of 400° F (477 K) and oxygen concentrations up to 21 percent.

2. Tests at 400° F (477 K) and 8-percent oxygen concentration exhibited a time limitation on the effectiveness of the oxidation inhibitor (induction period). For a new bearing, oxidation rate began increasing at about 8 hours. For a rerun bearing, the oxidation inhibitor was effective for at least 26 hours without a sharp increase in oxidation rate. This variation of the induction period was attributed to the presence of the antiwear additive.

3. Bearing torque increases during each test correlated with increases in lubricant viscosity.

4. Increases in viscosity were attributed to bearing operation in the presence of oxygen. Tests with the bearing not rotating produced relatively small increases in viscosity.

5. For the uninhibited synthetic paraffinic oil, both viscosity change and total acid number increased as oxygen concentration increased. A higher oxidation rate at higher oxygen concentrations was indicated.

Lewis Research Center,
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